Atlas of nuclear isomers and their systematics

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Abstract

Isomers can be viewed as a separate class of nuclei and offer interesting possibilities to study the behavior of nuclei under varied conditions of excitation energy, spin, life-time and particle configuration. We have completed a horizontal evaluation of nuclear isomers and the resulting data set contains a wealth of information which offers new insights in the nuclear structure of a wide range of configurations, nuclei approaching the drip lines etc. We now have reliable data on approximately 2460 isomers having a half-life ≥ 10 ns. A few of the systematics of the properties of nuclear isomers like excitation energy, half-life, spin, abundance etc. will be presented. The data set of semi-magic isomers strongly supports the existence of seniority isomers originating from the higher spin orbitals.

1. Introduction

The nuclear isomers are the excited meta-stable nuclear states. Large number of experimental and theoretical studies of isomers have been reported during the past few decades. The isomers provide a unique window into the nuclear structure properties in unusual situations. New isomers are being observed at a rapid pace, as it is now possible to measure the half-lives, ranging from picoseconds to years, in this new age of radioactive beams and modern instrumentation. Nuclear isomers are also known to have many useful applications and some of them promise to have still newer applications.

Our “Atlas of Nuclear Isomers” [1] lists more than 2460 isomers with a lower limit of half-life at 10 ns. It is quite interesting to look for the various regions in the nuclear chart where isomers exist. The answer to the question why, may be answered by a study of their properties and the underlying physics. We have, therefore, tried to systematize their various properties in a number of ways.

2. Types of Isomers

On the basis of the hindrance in decay, the nuclear isomers may now be classified into five types. The most common are the spin isomers. The other types are the K-isomer, the fission isomers and the shape isomers [2]. The fifth category, now increasingly recognized, is that of the seniority isomers.

Spin isomers occur due to the difficulty in meeting the spin selection rules in their associated decay. Shell model dictates that most of the spin isomers will occur near the magic numbers. K-isomers exist due to the large change in K, where K is the projection of the total angular momentum on the symmetry axis. K becomes a good quantum number for axially deformed nuclei. When a nucleus is trapped in the secondary minimum at a super-deformed shape in the path of fission, it may decay via spontaneous fission or/and decay back to the first minimum, and is known as fission/shape isomer.

Seniority isomers are mainly found in the semi-magic nuclei, where the seniority becomes a good quantum number due to the dominant role of the intruder orbital in the respective valence space. The matrix elements of the even tensor operator between the same seniority states vanish near the mid-shell, leading to the seniority isomers [3]. For example, the 10^+ and the $27/2^-$ isomers in the Z=50 isotopic and the N=82 isotonic chains behave as seniority isomers after the mid-shell, having seniority v=2 and 3 configurations in the $h_{11/2}$ intruder orbital respectively [4, 5].

3. Systematics

We present several systematics of the fundamental isomeric properties and the underlying physics. Nuclear isomers mostly decay via gamma decay, known as isomeric transition (IT). They can also decay via other decay modes as shown in Fig. 1, like beta decay (β), alpha decay (α) or spontaneous fission (SF) and proton decay (p).

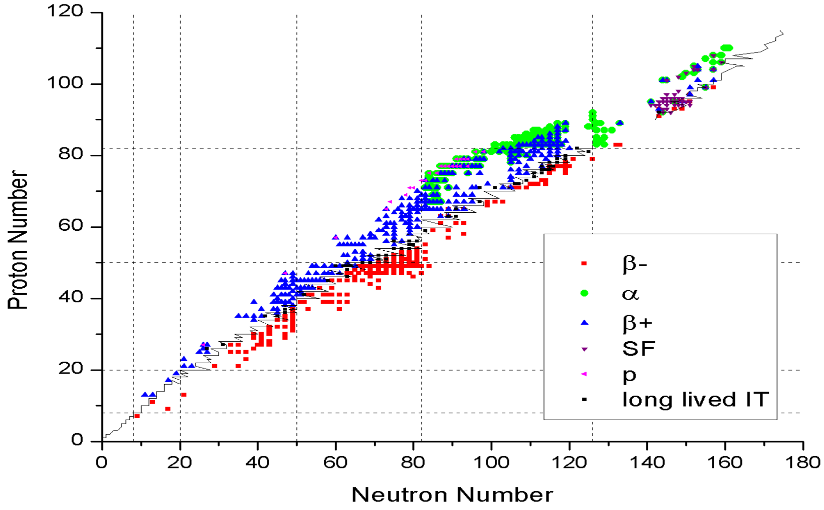

Fig. 1: The nuclear isomer chart with various decay modes, where the long lived IT decay isomers have a half-life cut-off at 1 *min*.

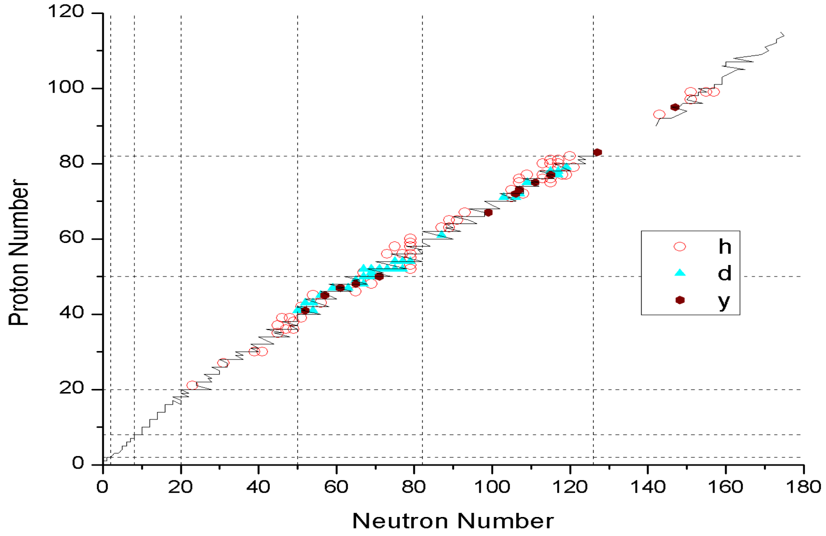

Fig. 2: The longest lived isomers having half-lives in *h* (hours), *d* (days) and *y* (years) as a function of (Z, N). These isomers lie on the line of stability.

We have plotted the “Nuclear Isomer Chart” with their various decay modes in Fig. 1, along with the long lived IT mode. The dashed lines are drawn at the spherical magic numbers of protons and neutrons respectively. The solid zig-zag line (in grey) represents the beta stability line, where the half-life cut-off of stable isotopes is taken at 10^{10} seconds. The isomeric nuclei, away from the beta stability line, and near to the proton/ neutron drip-line may dominantly decay via β^+/ β^--decay. The α-decay can be seen in heavier nuclei having Z > 82. One can easily observe that the SF mode is visible only in trans-actinides, as expected. The line has a gap at Z~84-94, and N~127-137 corresponding to the α-decaying radioactive nuclei. It is quite interesting to note that the nuclear isomeric chart also has the same gap, separating the two continents of isomers. We have also plotted the longest-lived isomers in the *h* (hours) to *y* (years) range, in Fig. 2, which mostly lie on the line of stability.

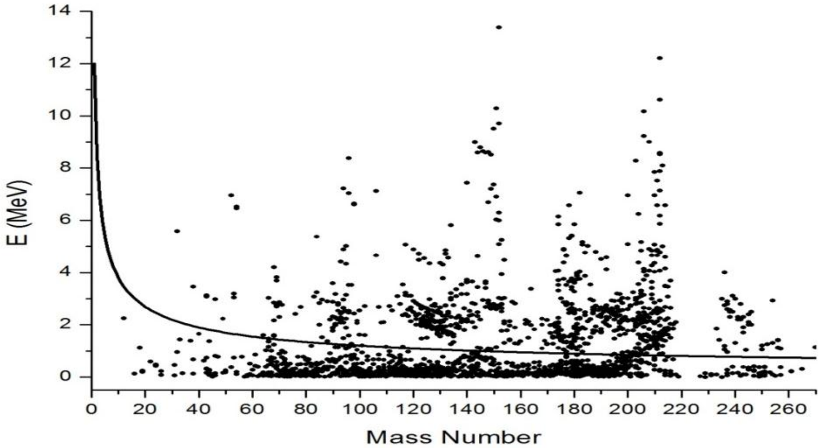

Fig. 3: The variation of the isomeric excitation energies with mass number *A*. The solid curve represents the pairing gap parameter $\Delta=12/\sqrt{A}$, which is observed to pass through the gaps.

We plot the variation of the isomeric excitation energies with mass number *A* in Fig. 3. The solid curve represents the variation of pairing gap $\Delta=12/\sqrt{A}$, where *A* is the mass number. We find that the solid line passes through the gaps between the zero/one-quasiparticle isomers and the two/three-quasiparticle isomers, which requires the one proton/ neutron pair break up in the even-even and odd-A isomeric nuclei respectively. There are some cases around the spherical magic numbers which fall within the gap. The separation of isomers by the pairing gap is very distinct and useful in classifying their quasiparticle structure.

We have separately plotted the occurrence of high-spin $11/2^-$, 10^+, and $27/2^-$ isomers in the nuclear chart in Fig. 4, 5 and 6, respectively. We notice that most of the isomers neatly cluster around and in between the particle and hole regions corresponding to the $h_{11/2}$ orbital, shown by the solid and dashed lines, respectively. The spin $11/2^-$ originates from the unique-parity $h_{11/2}$ orbital and low excitation energy suggests that they mostly have a 1-qp configuration. There are five cases far from this cluster, which lie around N=153 with a few hundred keV excitation energy. These cases too have a 1-qp structure, which probably originate from the projection of the next $j_{15/2}$ intruder orbital, and are possibly the K-isomers.

The 10^+ and $27/2^-$ isomers mainly come from the 2-qp and 3-qp structure in the intruder $h_{11/2}$ orbital except some cases. The two cases in the 10^+ isomers lie very low in mass region, having 6.5 MeV of isomeric excitation energy, and should have ~6-qp structure. There are also six more cases, of which four lie on the Z=82 line and the other three lie on the N=126 line, with one common doubly-magic ^{208}Pb nucleus. Therefore, the 10^+ isomers at Z=82, N=108-112, and 126 also have the many-qp structure, but not due to the $h_{11/2}$ orbital. The 10^+ isomer in ^{208}Pb has a high isomeric excitation energy of ~5 MeV, due to the doubly shell-closure. One case in $27/2^-$ isomer has Z=85 and N=128, again beyond the scope of the $h_{11/2}$ orbital. It has excitation energy of 1.3 MeV only, far less than required for core breaking, implying a many-qp structure.

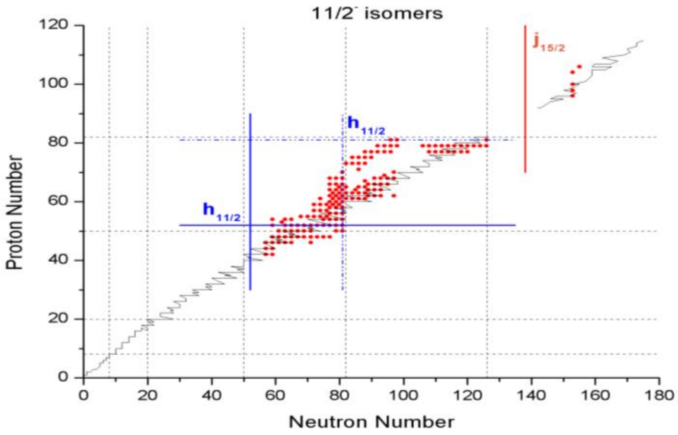

Fig. 4: Occurrence of the $11/2^-$ isomers throughout the nuclear landscape. The solid and the dashed lines depict the approximate particle and hole occupancies for the respective orbital shown in the figure.

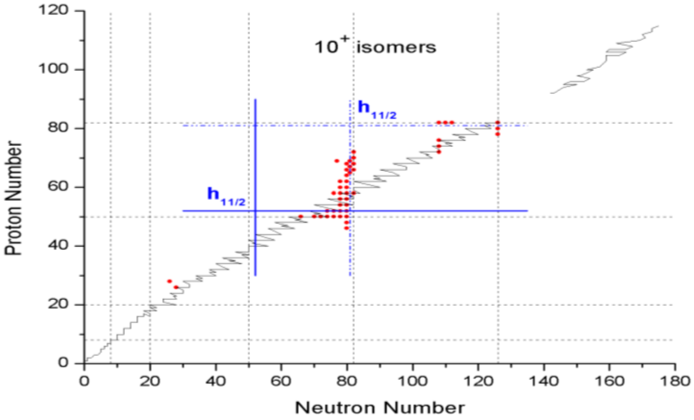

Fig. 5: Same as Fig.4 but for the occurrence of the 10^+ isomers.

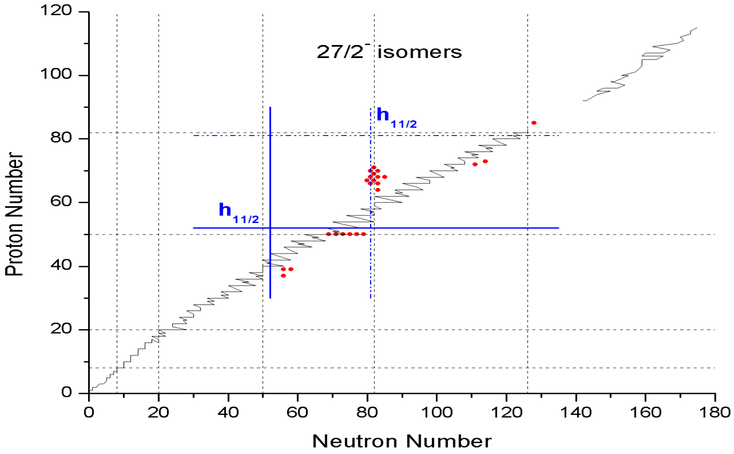

Fig. 6: Same as Fig.4 but for the occurrence of the $27/2^-$ isomers.

We have compared the $11/2^-$, 10^+ and $27/2^-$ isomers common to the Z=50 and N=82 chains in Fig. 7. The Z=50 isomers occur due to the valence neutrons while the N=82 isomers occur due to the valence protons. It is quite interesting to note that the experimental energy systematics for all these seniority isomers is almost identical irrespective of the valence proton/neutron space. The charge independent behavior of nucleon-nucleon interaction is also visible, so that the isomers of neutron-rich isotopes behave very similar to those of the neutron-deficient isotones. The relative energy gap between the $10^+/27/2^-$ isomers and the 0^+ ground state/$11/2^-$ isomer shows an energy transition from ~4 MeV to ~3MeV around the middle of the valence space. The $10^+/27/2^-$ isomers follow each other very closely, after the mid-shell, due to the dominant role of the intruder $h_{11/2}$ orbital. Large scale shell model calculations are able to reproduce and validate these identical systematics for both the chains [5].

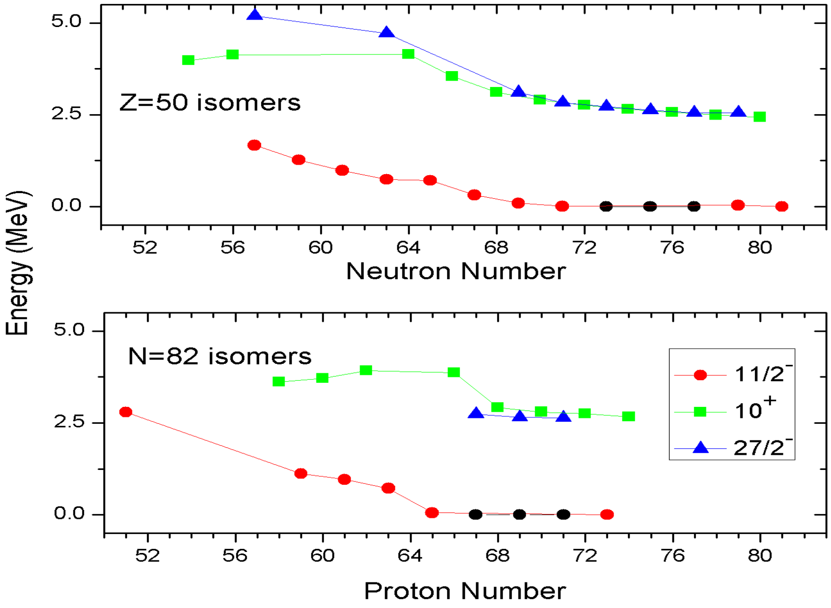

Fig. 7: The experimental excitation energy systematics of the $11/2^-$, 10^+ and $27/2^-$ isomers common to the Z=50 isotopic and N=82 isotonic chains.

4. Summary

A few of the systematic features of the isomers have been presented in terms of the fundamental properties like half-life, spin-parity, energy, etc. Some of them are very new, and enable us to explore the physics behind them. Many of these universal and novel features of the isomers may open new perspectives in the field.

References

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